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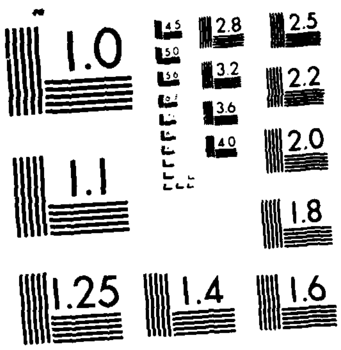

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CONTRACTOR REPORT

**SPACECRAFT CONTAMINATION FROM A CHEMICAL LASER RING-JET
A PROGRESS REPORT**

Joseph Falcovitz

November 1985

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Superintendent

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Provost

The work reported herein was performed for the Naval Postgraduate School by Dr. Joseph Falcovitz under Contract Number N62271-84-M-3345. The work presented in this report is in support of "Rarefied Gas Dynamics of Laser Exhaust Plumes" sponsored by Strategic Defense Initiative Office/Directed Energy Office. The work provides information concerning backscattering to the spacecraft from a multispecies laser exhaust plume. The project at the Naval Postgraduate School is under the cognizance of Distinguished Professor A. E. Fuhs who is the principal investigator.

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The purpose of this report is to present a review of work done at the Naval Postgraduate School (NPS) on the contaminating backflow from the exhaust plume of a chemical laser mounted on an earth-orbiting spacecraft. Various mechanisms that may give rise to a backflow are outlined; primarily: thermal backscattering, ambient scattering, and viscous effects. Detailed studies have been conducted at NPS on thermal backscattering. They are reviewed in this report, concluding that corrosive fluxes (HF,DF,F) due solely to this effect are negligible. The flux of light species (He,H_2), however, is significant.

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ACKNOWLEDGEMENT

This work constitutes a review of effects that may lead to HF laser self-contamination by its exhaust, rather than detailed studies of any specific effects. The cooperation of Professor Allen E. Fuhs in formulating these ideas through lengthy discussions was instrumental and it is gratefully acknowledged.

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1. INTRODUCTION

A proposed earth-orbiting chemical laser system is based on the following design concept: the spacecraft is of a cylindrical shape; the laser beam emerges in an axial direction through one end, where it may be obliquely reflected by an externally mounted set of adjustable mirrors. Lasing is obtained from a chemically reactive gaseous mixture (Fluorine, Hydrogen, Deuterium, Helium) flowing in an outward radial direction and exhausting as an underexpanded supersonic ring-jet. The nozzle is located about midway along the spacecraft.

An isentropic non-viscous idealized analysis of the jet indicates that the plume boundary will stay clear of the spacecraft, by virtue of the fact that the corresponding Prandtl-Meyer turning angle is well below 90°. However, deviations from this idealized gasdynamic model may give rise to some secondary backflow, leading to possible contamination of the spacecraft and its immediate environment. This contamination may well turn out to be a significant factor in the design evaluation of such space systems. We have taken up the study of those contaminating secondary flow effects, with the intent that it may contribute to future design efforts.

The scope of this report is twofold:

(a) Outline various physical phenomena which may contribute to the formation of a secondary backflow. There is a related field of spacecraft technology which may be helpful: rocket plume contamination [1].

(b) Review the work done at NPS on this subject to date (Fall 1985).

2. OUTLINE OF BACKFLOW-GENERATING PHENOMENA

We outline a number of physical effects which may lead to significant backflow from the laser exhaust plume. So far, only the first one (thermal backscattering) was studied in some detail by us [2], [3], and [6]. The others will be considered in the future.

2.1 Thermal Backscattering

This mechanism is the simplest conceivable source for backscattering, since it does not involve viscous boundary effects or any other deviations from the ideal gasdynamic model of a free ring-jet. The backscattered molecules are those few coming from the tail of the (presumably Maxwellian) velocity distribution function and having a backward-facing thermal velocity of sufficient magnitude to overcome the supersonic flow velocity. They emanate from the fringes of the exhaust plume. The thermal backscattering is depicted schematically in Figure 2-1. Studies conducted so far at NPS (detailed reports are forthcoming), indicate that the flux of corrosive species (HF,DF,F) is so small that one may safely ignore thermal backscattering as a mechanism for generating a contaminating backflow. The flux of lighter species (H, H_2, D, D_2, He) however, will be much larger (by many orders of magnitude) and may be of some significance to spacecraft design and operation.

2.2 Ambient Scattering

Ambient backscattering results from the fact that ambient molecules enter the exhaust jet with a velocity of about 8 km/sec, which is much higher than the flow velocity in the exhaust jet (Figure 2-2). (Figure 2-2 shows the relative velocity vector parallel to spacecraft axis; other orientations are likely to occur). Some jet molecules will be backscattered towards the spacecraft, and our task will be to assess their flux. The significance of both thermal and ambient backscattering is related to the fact that unlike the viscous effects, these effects are inherent to the laser system and cannot be "designed out". A good estimate of the magnitude of ambient backscatter is, therefore, indispensable. Since the jet mass flux is much higher than that of ambient molecules, only a small fraction of the jet molecules will collide with an ambient molecule in the vicinity of the spacecraft. Likewise, thermally backscattered molecules also constitute a small fraction of the jet flux. Hence, these two backscattering mechanisms can be considered as independent, and the total backflow would be a superposition of thermally and ambient backscattered molecules.

2.3 Viscous Effects

Viscous effects are paramount in the boundary layer, especially near the nozzle lip (Figure 2-3). Their significance as a source for contaminating backflow is proportional to the thickness of the boundary layer. Due to the location of a sonic line within the boundary layer (Figure 2-3), there will be a "subsonic spillover" flow around the nozzle lip. This is a continuum flow regime, and it does not depend in any way on the Knudsen number being large. However, as pointed out by Bird [7], the region of interest around the nozzle lip, may in typical cases be no larger than 10 to 100 mean free paths, so that

we are dealing in effect with a rarefied viscous flow, and the proper governing equation is the Boltzmann equation. Such visous effects have been studied extensively in connection with rocket plume contamination [1]. It should be pointed out that for a chemical laser, this source of contamination may be eliminated by introducing a flushing stream of inert gas (perhaps Helium) into the boundary layer upstream from the nozzle lip, or by an expanding-step design of the nozzle lip.

2.4 Bow Shock in Air

When the orbit altitude is sufficiently low (probably less than about 100 km), an air shock wave will form ahead of the spacecraft. The shock wave is the result of the exhaust plume. When this happens, the exhaust plume is subject to an influx of ambient air of quite different characteristics from the uniform molecular stream that was assumed for outer space (see Section 2.2 above). The situation is depicted in Figure 2-4. The air shock has been studied for the operation of large rockets in low-altitude orbits [8]. An area is defined by the ratio of rocket thrust to dynamic pressure of ambient air relative to the spacecraft; the area is

$$A = \frac{\text{"ROCKET THRUST"}}{\frac{1}{2}\rho_0 V_0^2} \quad \frac{I_{sp}\,\dot{m}}{\frac{1}{2}\rho_0 V_0^2} \tag{1}$$

As shown in equation (1), rocket thrust is equal to product of specific impulse and mass flow rate. The laser does not have thrust; the connection between lasers and rockets in space is the mass flow rate. A laser does not use I_{sp} as a performance parameter; however, one can relate I_{sp} to exhaust velocity by equation (2) through the gravity acceleration g:

$$V_e = I_{sp} g \tag{2}$$

The altitude at which a bow shock can be supported depends on the mass flow rate, $\dot{m}$. Whenever

$$Kn = \frac{\lambda_o}{A^{1/2}} < 0.03 \tag{3}$$

A bow shock wave is expected. The relevant Knudsen number is Kn . When Kn is less than approximately 0.03, effects of continuum gasdynamics occur. When Kn as defined by equation (3) is higher than 0.1, the flow is rarefied, and a bow shock does not occur.

2.5 Startup and Shutdown Transients

If a single-shot period is about 1 second (Figure 2-5), these transients may well constitute a significant fraction of the total laser operating time. Some shutdown work on rockets [1] indicated that a relatively long decay time is observed, probably due to degasing of adsorbed species after shutdown. Perhaps some inert gas flushing - both before and after firing - might eliminate much of the contaminating species in this instance.

2.6 Plasma Effects

It is conceivable that since the spacecraft is charged, it may significantly alter the flow of ionized exhaust molecules (in particular electronegative species such as HF^- and F^-) through electrostatic attraction or repulsion. Also, the exhaust plume interacts with the ambient plasma, thus leading (possibly) to a change in the charging pattern of the spacecraft [9]. At equilibrium the flux of electrons equals the flux of positively-charged ions. If spacecraft has zero potential relative to the plasma, the current densities are given by

$$J_{io} = \frac{q_i N_i}{2} \left(\frac{2kT_i}{\pi m_i}\right)^{1/2} \tag{4}$$

where: q_i is charge of ith species (coulomb)

N_i is number density of i'th species (m^{-3})

k is Boltzmann's constant

T_i is translational temperature (K)

m_i is mass of ith species (kg)

$(\ )_0$ refers to zero potential for spacecraft (volts)

Equation (4) assumes a Maxwellian velocity distribution. Due to the fact that $m_{ion} >> m_e$, the current due to ions is very small. The spacecraft charges negatively until the flux of electrons is reduced due to electrostatic repulsion. This is a simplified version of spacecraft charging [9] but gives the essence of the process.

The laser exhaust plume can alter three variables in equation (4); these are n_i , T_i and m_i . The number density, n_i , can be varied by interaction between ambient plasma and exhaust species. One example would be

$$F + e^- + M \rightleftarrows F^- + M \qquad (5)$$

where: F is a fluorine atom

e^- is an electron

M is a third body

Because of low density, the forward reaction rate may be slow. The reaction of equation (5) changes n_e and n_F . Further, the charge associated with a highly mobile electron is converted to a high-inertia fluorine negative ion. Interaction between the ambient plasma and the exhaust can change T_i ; changes in T_i will alter the level of spacecraft charging.

3. OUTLINE OF RING-JET FLOW FIELD

In this chapter we review the work done to date on the laser exhaust flow field. The following qualitative description of this flow field may well

remain with us even as we proceed through more detailed and refined studies of various backscatter mechanisms.

At the inception of the present research effort [2], the laser exhaust flow field was envisioned as comprising of three domains of distinctly different flow regimes (Figure 3-1).

(a) An inner core of isentropic supersonic flow.

(b) An intermediate transition layer, containing both exhaust and ambient molecules.

(c) An almost collisionless outer cloud of exhaust and ambient molecules.

In the inner domain, which we now call the "Primary Plume", the flow is governed by the laws of continuum mechanics (ideally: non-viscous, isentropic compressible flow). In the outer domain - the "Secondary Plume" - the flow is assumed collisionless, and is appropriately governed by the collisionless Boltzmann equation. The Primary and Secondary Plumes are separated by a transition layer whose thickness is of the order of several mean free paths, where the laws of continuum mechanics have broken down and the flow is governed by the full Boltzmann equation.

How were these concepts formulated into computer models for the determination of the Primary and Secondary Plumes? The idea was to do so via a two-step approach, beginning with the Primary Plume and proceeding outward through the transition layer to the Secondary Plume [2]. This approach was prompted by the observation that due to the supersonic flow velocity in the jet, the molecular flux at any fixed boundary is very nearly a pure outflow flux. Thus, the Primary Plume can be computed while neglecting any backward flux at the boundary with the transition layer. The boundary conditions for the transition flux are correspondingly approximated as the supersonic influx at

the boundary of the Primary Plume. At the outer boundary - the Free Molecular surface - the backflow is likewise negligible, and the boundary conditions are pure outflow. However, we note that portions of the Free Molecular surface are subject to impingement of ambient molecules, so there is an appropriate influx boundary condition there. Let us proceed to consider this flow field in more detail, both in the continuum and rarefied flow regimes.

The crudest conceivable simplification of the transition layer is to lump it all into a single surface of continuum breakdown, thus replacing the gradual transition from continuum to free molecular flow by an abrupt change. The influx into the Secondary Plume is then approximated by the molecular effusive flux from the breakdown surface, defined by equation (6). These ideas were first put forward by Noller [5], and were adapted by McCarty at NPS to the laser exhaust problem [6]. McCarty [6] showed that for typical laser operating conditions, the length of the lip-centered rarefaction fan that contributes significantly to thermal backscattering is no more than about 0.1 m, while the spacecraft diameter is assumed to be about 5 m. Consequently, a planar rarefaction fan (Prandtl-Meyer) is a reasonable approximation to the actual ring-fan, so that the breakdown surface and effusive flux can be expressed by simple closed-form expressions. The flux arriving at the spacecraft was then obtained by straightforward integration [6]. Presently, this work is about to be redone with a slight modification, allowing for the separate computation of the flux of the various species (mainly He, DF, HF). It is expected that the flux of heavier-than-average species (such as HF) will be smaller by several orders of magnitude relative to the flux of average-weight molecules computed by McCarty [6].

An alternate approach to the computation of thermal backscattering was also formulated. It is a less crude physical model for the continuum breakdown, in

that it does not assume any breakdown surface as in McCarty's model [6]. Here, it is assumed that any molecule will be backscattered, provided two conditions are fulfilled: (a) It originates from the tail of the (presumably Maxwellian) distribution function with a backward-facing thermal velocity. (b) It does not collide with any jet molecule on the way to the spacecraft. When explicit integrals for the distribution function of the backscattered molecules were written down (assuming that the continuum Prandtl-Meyer solution extends all the way to the vacuum), it turned out that they also constituted a formal solution to a BGK-type approximation of the Boltzmann equation, which lends more credence to this effusion layer model.

3.1 The Primary Plume

An idealized gasdynamic model for the Primary Plume was formulated as follows: The flow was assumed stationary, compressible, nonviscous and isentropic. The fluid was assumed to be an ideal gas, with a constant specific heat ratio γ . Boundary conditions were simplified by assuming a uniform nozzle outlet flow (generally supersonic), and an ambient pressure along the Primary Plume boundary. This flow field was computed numerically using a standard method-of-characteristics finite difference scheme. A code by the name of AXSYM was written, capable of computing both ring-jets and plane-symmetrical jets [2].

As a prelude to the actual analysis of the Primary Plume flowfield in a ring-jet, some insight to the nature of the various flow regimes that may arise in an underexpanded jet, was gained by considering the plane-symmetry case via a hodograph transformation [3]. A classification of jets going from "Subcritical" to "Critical" and to "Supercritical", with increasing the exit-to-ambient pressure ratio, was suggested by analyzing the free-jet expansion in the hodograph representation [3]. Basically, this classification

derives from the observation that the centered rarefaction waves fanning out symmetrically from both nozzle lips when the jet is moderately underexpanded, intersect along the centerline giving rise to an inner core of lower-than-ambient pressure. Downstream from that core, the flow undergoes re-compression via a symmetric set of two centered compression fans. The ensuing free boundary (defined as the line of ambient pressure), thus exhibits the familiar diamond pattern of alternating expanding and contracting segments. When the exit-to-ambient pressure ratio is sufficiently high, the hodograph analysis indicates that the inner core will reach zero pressure, and the jet is then defined as "critically underexpanded" [3]. For yet higher exit-to-ambient pressure ratios, the jet is "highly underexpanded", having a monotonically divergent boundary [3]. At altitudes of 200 km or more, the ambient pressure is less than 10^{-7} [kPa], and a typical laser exhause having an exit pressure of about 10^{-1} [kPa], would definitely be "highly under-expanded". This is an important conclusion. It implies that in considering the Primary-to-Secondary Plume transition layer, one may assume an ever-widening jet boundary, discarding the possibility of re-compression in the Primary Plume, and the corresponding "diamond-shape" boundary.

3.2 The Transition Layer

The key to an estimate of the Secondary Plume flow field is the determination of the rarefied flow in the transition layer (Figure 3-1). As a simplification, we assume a distinct boundary between the Primary Plume and the transition layer, which we name the "Breakdown Surface". It is assumed to be the outermost surface on which the continuum description of the flow is still valid. Following Bird's suggestion ([4], section 8.3), the Breakdown Surface is defined as the surface of constant gradient-related Knudsen

number:

$$B = \frac{U}{\nu} \frac{1}{\rho} \left|\frac{d\rho}{ds}\right| \tag{6}$$

Where ν is the local collision frequency, s is a coordinate along the local streamline, ρ and U are the local densities and flow speed. A value of $B \cong 0.05$ is recommended by Bird as a typical choice for a Breakdown Surface. The choice of an outer boundary to the transition layer is motivated by expedience rather than by necessity. It is desirable to restrict the (computationally expensive) solution of the Boltzmann equation to the collision-dominated flow in the transition layer and approximate the flow in the Secondary Plume as collisionless. The "Free-Molecular" surface is thus defined as the outer boundary to the transition layer, beyond which the collision frequency is sufficiently small to be neglected altogether.

An important observation is now made regarding the interaction of the oncoming ambient molecules with the exhaust jet. Since the mean free path for free ambient molecules is a few hundred meters or more [2], and since the density in the secondary plume is presumed sufficiently low to neglect all collisions there, the ambient molecules will undergo collisions with exhaust molecules only within the transition layer. Thus, both the thermally backscattered molecules and jet molecules scattered by ambient influx, originate at the transition layer.

Naturally, after completing the task of continuum flow computation of the Primary Plume, attention was focused on tackling the transition layer flow field. The method chosen was a Direct Simulation Monte Carlo ([2], [4]) computation. It was determined that the region of significance for the Secondary Plume was the centered rarefaction wedge-shaped region that fans out of the nozzle lip. A code by the name SIMUL was written for that wedge-shaped

region, with the intention of computing both thermal and ambient backscattering with it [2]. Presently, it was decided to suspend any further work with this code for the following reason. The flux of both thermal and ambient scattered molecules being a very small fraction of the jet flux, the two scattering mechanisms can be considered as uncoupled phenomena. The total backflow would then be a superposition of these two fluxes. As a first step it was decided to take a close look at thermal backscattering, and the computer model for that effect is not necessarily the same one used for obtaining ambient scattering. In fact, it turns out that while the SIMUL Monte Carlo simulation may still be found adequate for ambient scattering, (and that matter will be taken up in the future), it seems inadequate for evaluating thermal backscattering. The reason is that the maximum conceivable total sample size in SIMUL is about 10^8 (10^4 molecules x 10^4 time steps), while the fraction of molecules likely to be thermally backscattered is probably less than 10^{-10} ($\exp(-M^2)$ where the Mach number M is typically 5 or more). Hence, thermal backscattering can be computed from the Monte Carlo solution only indirectly, by defining a temperature to the sampled distribution function (through a best-fitting Maxwellian), and computing the flux of those molecules at the far tail of the distribution function whose backward-facing thermal velocity exceeds the flow velocity. The fact that a Direct Simulation Monte Carlo does not adequately describe phenomena related to molecules coming from the tails of the distribution function, has been pointed out by Bird himself ([4], section 8.3).

Since we are not aware of any modified Monte Carlo formulation which would remedy this shortcoming, we opted for direct physical models describing the thermal backscattering from the transition layer.

4. CONCLUDING REMARKS

The results obtained so far in our study of the exhaust flowfield are:

4.1 The free molecular backflow due to both thermal and ambient scattering originates at the region where transition from continuum to collisiorless flow takes place.

4.2 The thermal contribution comes from the near part of the nozzle-lip-centered rarefaction fan (about 0.1 m or less). It is very small, and the flux of corrosive specie (HF,DF,F) may be negligibly small. Detailed reports on modeling this effect and quantitative results are forthcoming.

4.3 The next step to be taken up in our study is ambient scattering.

4.4 Additional effects that may contribute to contaminating backflow, or may otherwise alter the immediate spacecraft environment interfering with its operation, were pointed out by us (2.2, 2.3, 2.4, 2.5, 2.6 above). It should be emphasized that the task of thinking out other relevant phenomena remains with us even as we proceed with detailed studies of the laser exhaust flow field.

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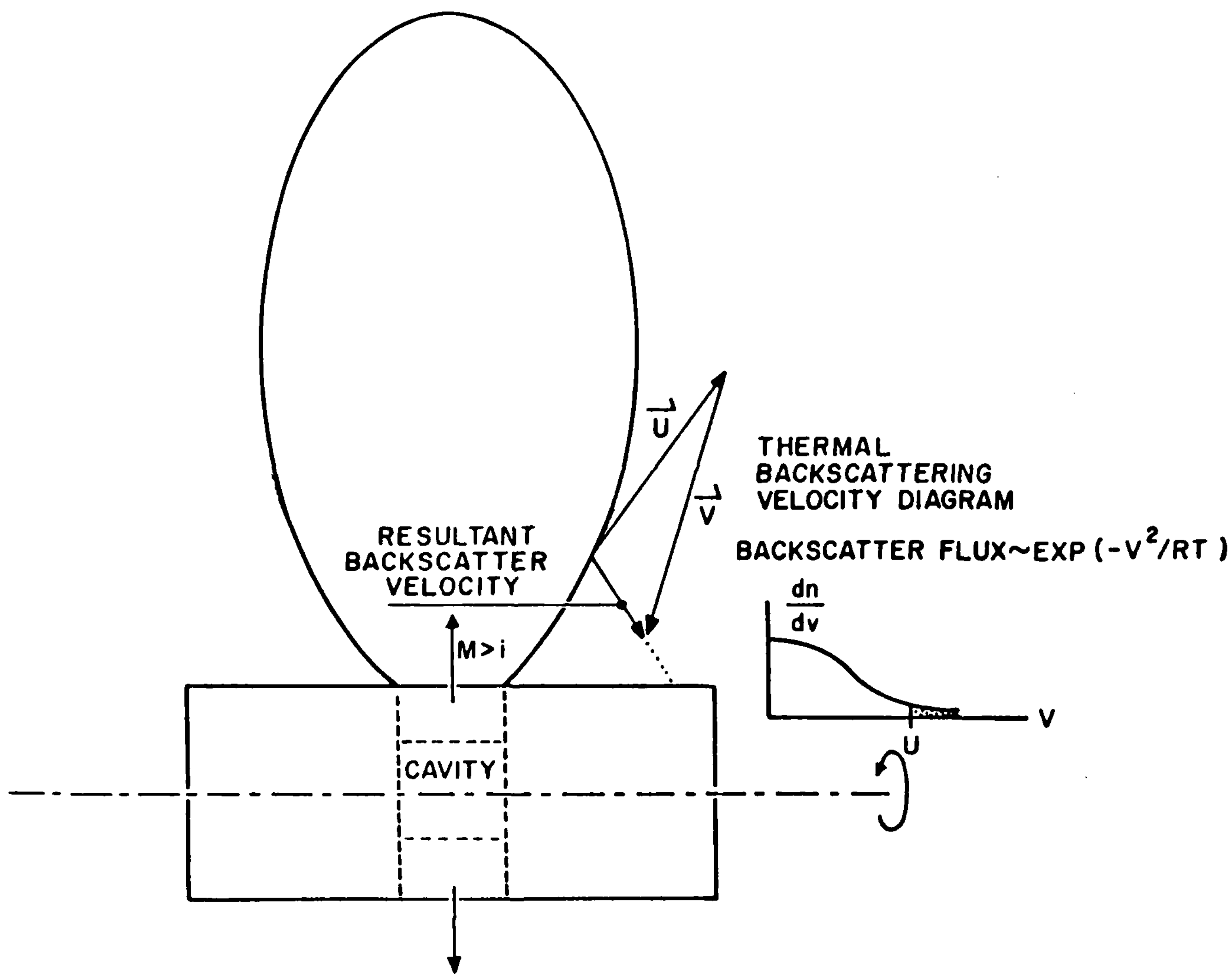


FIGURE 2-1: THERMAL BACKSCATTERING FROM LASER EXHAUST PLUME

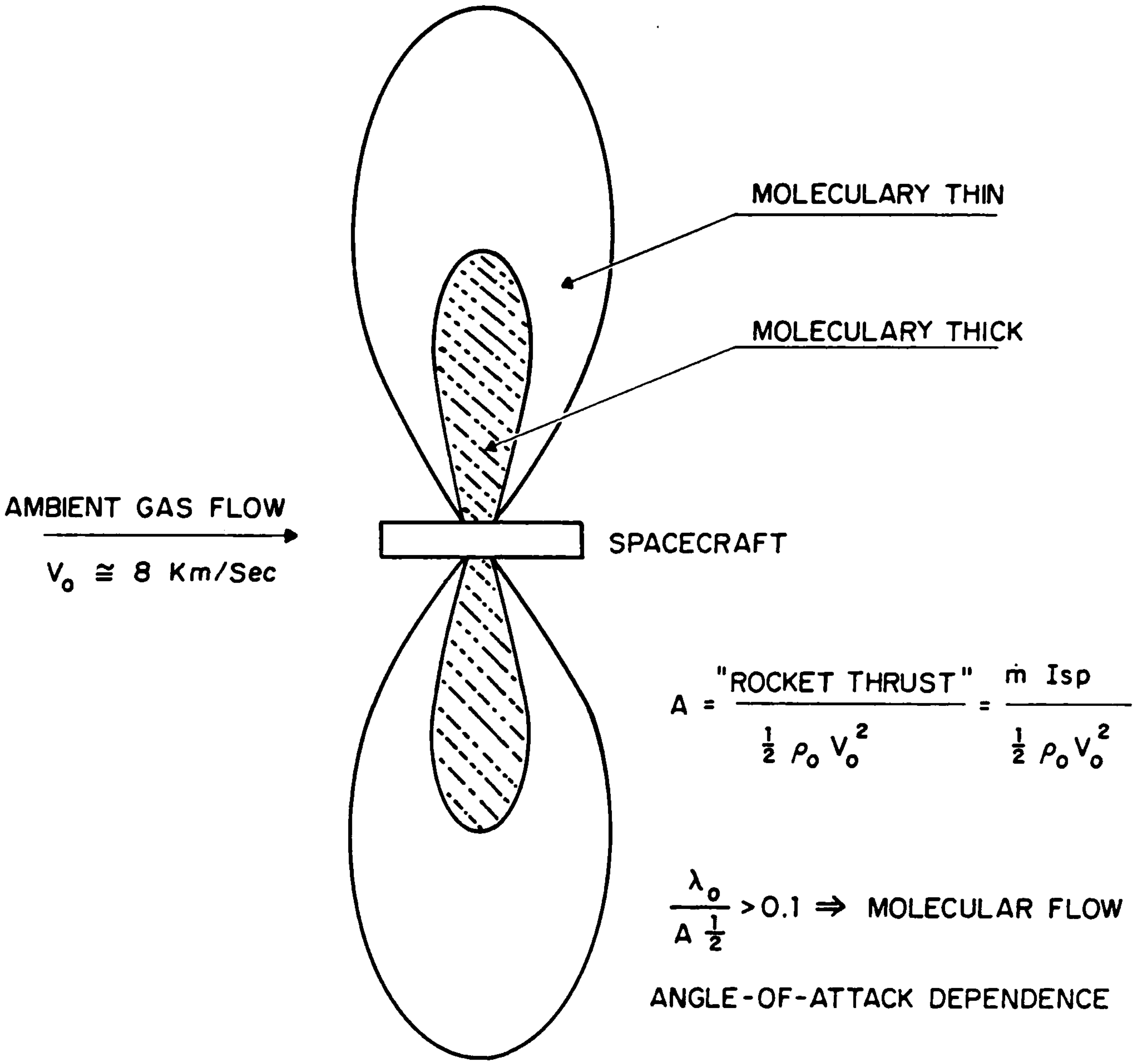
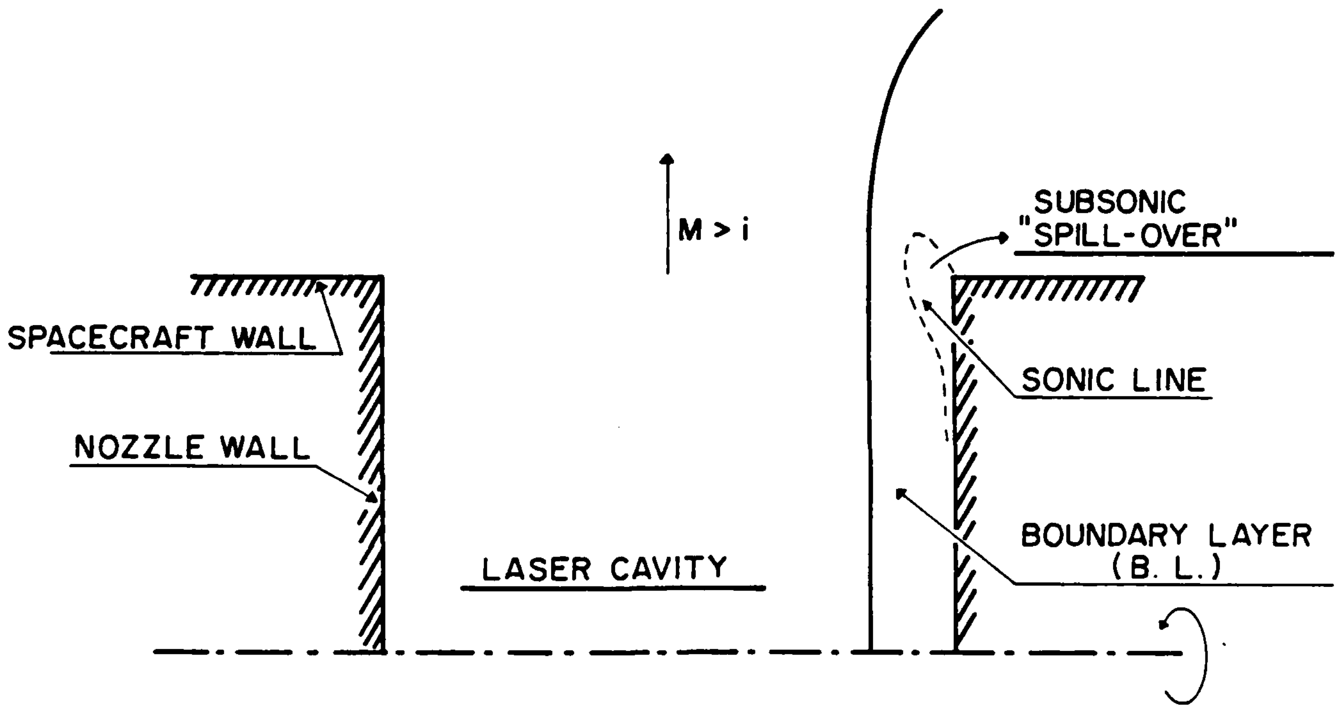


FIGURE 2-2: MOLECULAR FLOW OF AMBIENT GAS



POSSIBLE "SPILL-OVER" REMEDIES:

- FLUSH B. L. WITH INERT GAS
- REDESIGN NOZZLE LIP-CREATE GEOMETRIC BUFFER

FIGURE 2-3: VISCOUS EFFECT AT NOZZLE LIP

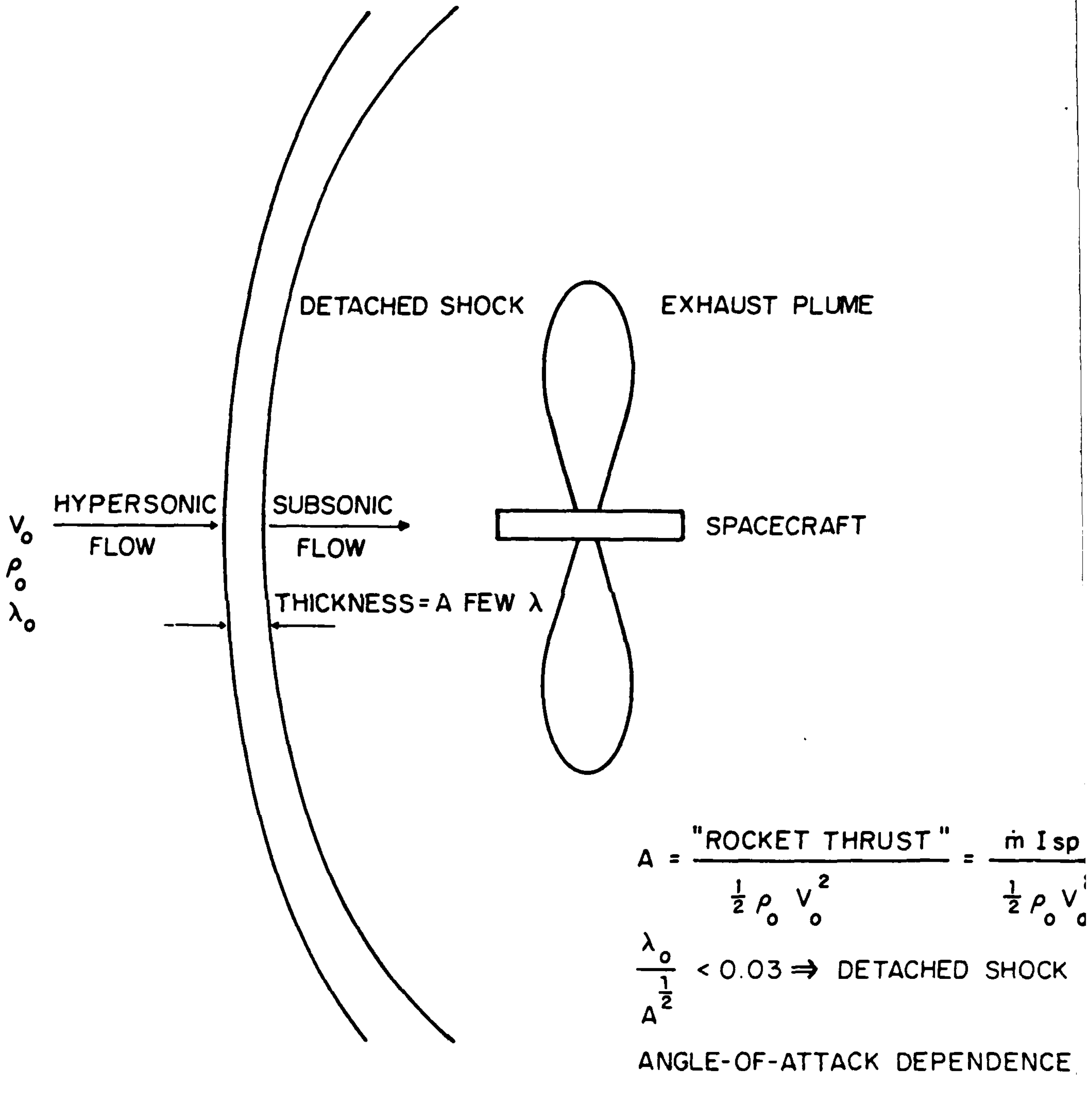


FIGURE 2-4: DETACHED SHOCK IN AMBIENT GAS

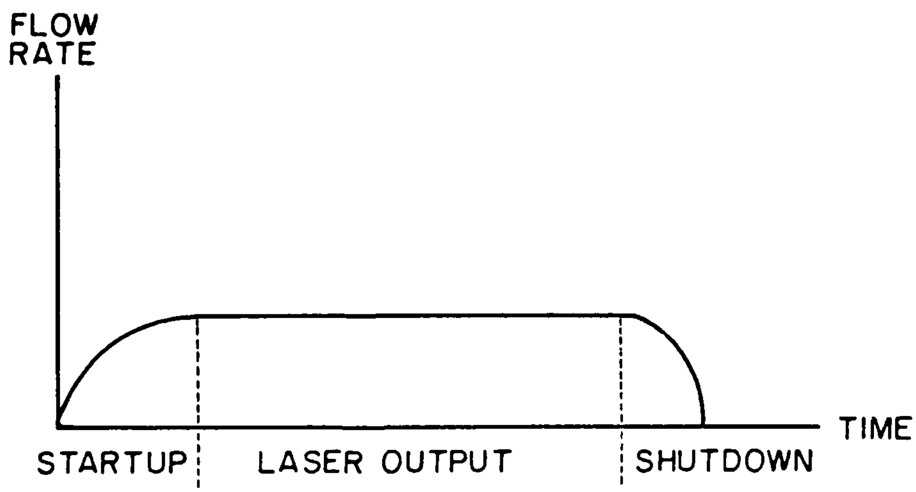


FIGURE 2-5: STARTUP AND SHUTDOWN TRANSIENTS

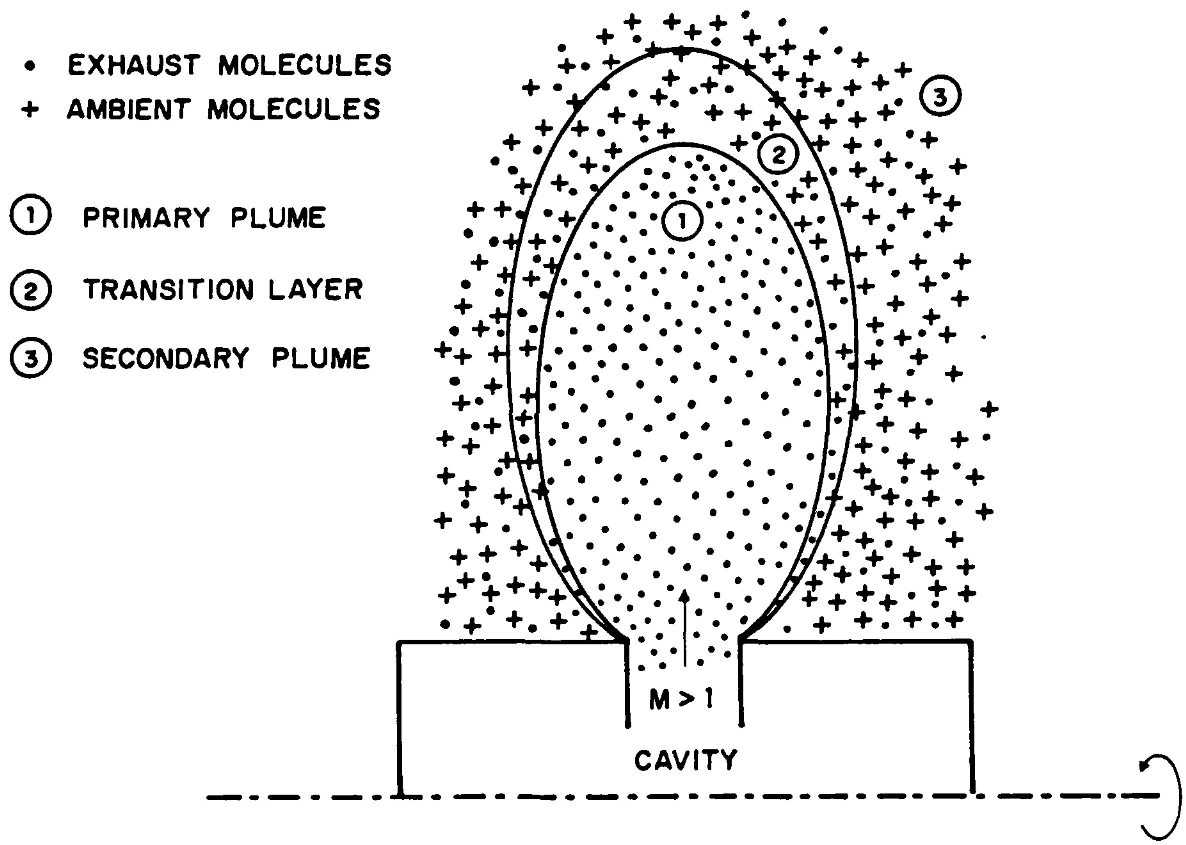


FIGURE 3-1: SCHEMATIC DESCRIPTION OF LASER EXHAUST FLOW FIELD

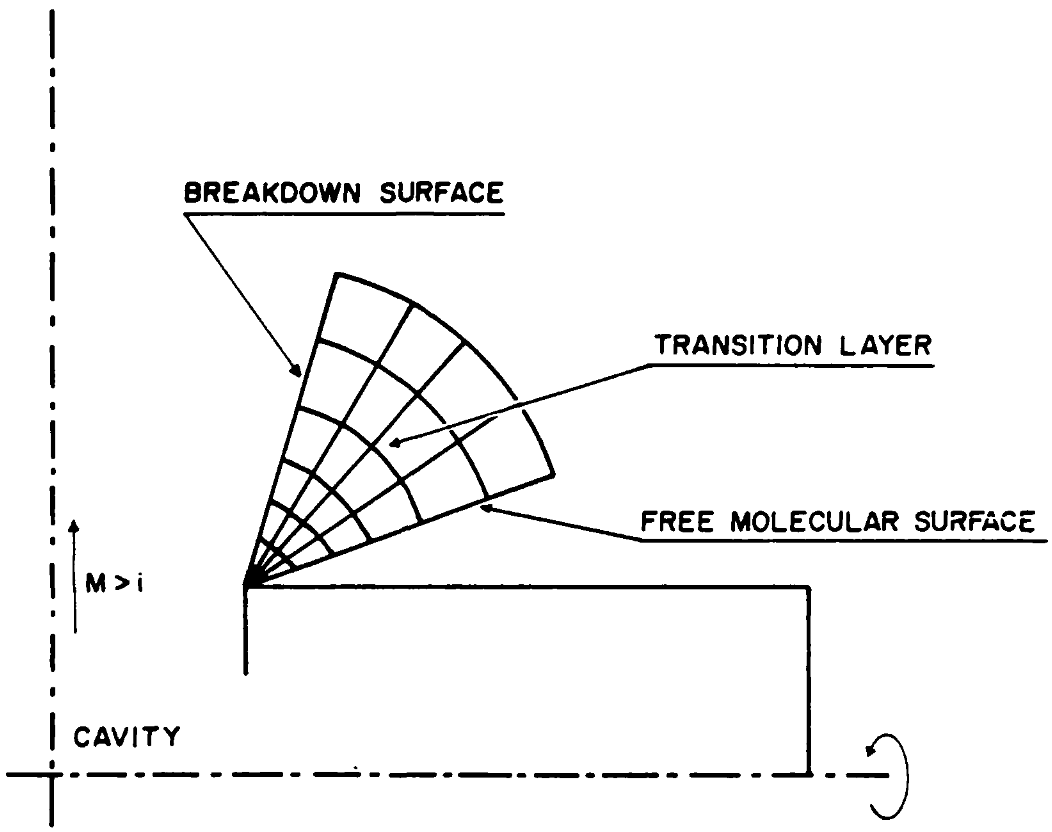


FIGURE 3-2: WEDGE-SHAPE APPROXIMATION TO THE TRANSITION LAYER (CODE SIMUL [2])

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8.	Associate Professor O. Biblarz Department of Aeronautics Code 67Bi Naval Postgraduate School Monterey, CA 93943-5100	1
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